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(12) # EUROPEAN PATENT APPLICATION

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(54) **Method and apparatus for measuring spectral content of LED light source and control thereof**

(57) Solid state illumination using closed loop spectral control. Light emitting diodes producing different colors (110, 120, 130) are mounted in close proximity to photosensors (150). Spectral content of the light emitting diodes is measured by the photosensors (150), and these measurements used to adjust light emitting diode currents to achieve the desired spectral characteristics.

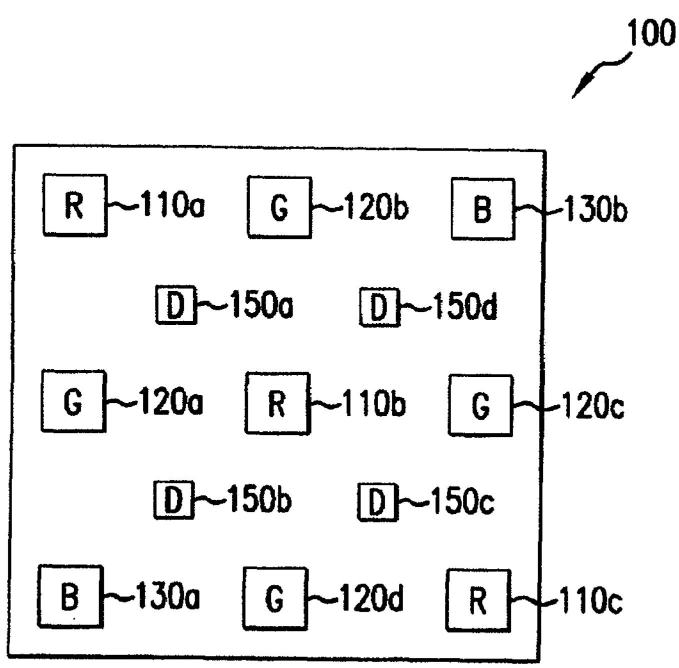

FIG.1

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Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention pertains to the field of solid state illumination, and more particularly to solid state illumination systems employing closed loop control to maintain spectral characteristics.

Art Background

[0002] High brightness Light Emitting Diodes (LEDs) have sparked interest in their use for illumination. LEDs have no moving parts, operate at low temperatures, and exceed the reliability and life expectancy of common incandescent light bulbs by at least an order of magnitude. The main drawback in implementing LED based light sources for general illumination purposes is the lack of a convenient white-light source. Unlike incandescent light sources which are broadband black-body radiators, LEDs produce light of relatively narrow spectra, governed by the bandgap of the semiconductor material used to fabricate the device. One way of making a white light source using LEDs combines red, green, and blue LEDs to produce white, much in the same way white light is produced on the screen of a color television.

[0003] Combining light from blue, red, and green LEDs of appropriate brightness yields a "white" light. The brightness of each LED is controlled by varying the amount of current passing through it. Slight differences in the relative amounts of each color manifests itself as a color shift in the light, akin to a shift in the color temperature of an incandescent light source by changing the operating temperature. Use of LEDs to replace existing light sources requires that the color temperature of the light be controlled and constant over the lifetime of the unit.

[0004] Some applications require more careful control of spectral content than others, and differing color temperatures may be desired for different applications. For example, spectral control is of extreme interest in applications such as lighting of cosmetics counters, and food outlets, while spectral control may not be critical in industrial lighting applications where reliability is more important.

[0005] There are two effects which make careful control of spectral content difficult. First is that the luminous efficiency of a given LED will not exactly match that of another LED manufactured by a nominally identical process. The second is that the luminous efficiency of a given LED, and its spectral content, may shift over the lifetime of the device.

[0006] The first problem may be addressed by testing, grading, and matching devices during manufacture. This testing is expensive, and does not address changes occurring with device aging.

[0007] What is needed is a method of automatically measuring the spectral content of a LED light source, and controlling the spectral content based on that measurement.

SUMMARY OF THE INVENTION

[0008] Spectral content of a solid state illumination source composed of Light Emitting Diode (LED) sources of different colors is measured by photosensors mounted in close proximity to the sources. The results of these measurements are used to control the spectral content by varying the current to the different color LEDs.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The present invention is described with respect to particular exemplary embodiments thereof and reference is made to the drawings in which:

Fig. 1 shows the layout of a solid state illumination device according to the present invention,

Fig. 2 shows the block diagram of an embodiment for the control circuit,

Fig. 3 shows the block diagram of an additional embodiment for the control circuit, and

Fig. 4 shows a simple switching converter.

DETAILED DESCRIPTION

[0010] Fig. **1** shows the layout of a solid state illumination device according to the present invention. While mounting LEDs and photosensors on the same substrate may increase manufacturing efficiency, such comounting is not necessary to practice the instant invention. Common substrate **100** holds light emitting diodes of different colors, and sensors for sensing emitted light. In this embodiment photodiodes are preferred, although any electrical device which produces a predictable varying electrical response to illumination may be used. In Fig. **1**, LEDs of three colors, red **(110a, 110b, 110c)** green **(120a, 120b, 120c, 120d)** and blue **(130a, 130b)** are mounted on the substrate, along with photosensors **150a, 150b, 150c,** and **150d.** Photosensors **150** are interspersed between LED chips **110, 120, 130** to collect "averaged" light. Incident light on photosensors **150** is mainly via scattering, and is relatively well mixed. Any layout which allows for the photosensors to collect incident light from the LEDs is acceptable.

[0011] A common substrate may also used to provide interconnections between the devices and control circuitry. In mounting the devices on the substrate, the substrate may be used to provide a common terminal (anode or cathode) with the devices mounted thereupon. It may be advantageous to use the substrate as a com-

mon terminal so as to reduce the number of connections. In some circumstances it may be advantageous to separate out the connections between LEDs **110, 120, 130** and photosensors **150,** so that the relatively large currents flowing through LEDs **110, 120, 130** do not interfere with the ability to measure the relatively small currents from photosensors **150.**

[0012] The number and arrangement of LED chips and sensor chips is determined to a great extent by the light output of the LEDs, and the light output needed. Given efficient and powerful enough LEDs, only one of each color would be needed. The photosensors are interspersed among the LED chips to collect averaged light.

[0013] When photodiodes are used as photosensors **150**, as in the preferred embodiment, they may be collected in parallel allowing automatic summation of the signals from each photodiode.

[0014] In operation, a desired spectral content is selected. This may be done in terms of equivalent color temperature. The spectral content of the operating set of LEDs is measured, and adjusted to match the desired levels.

[0015] In a first method of measuring spectral content, a calibration cycle is used in which the light flux of each LED color is measured and adjusted. In this method, photosensors 150 have useful and known response over the spectral range required. Each color of LED is illuminated independently for a brief period of time. The light output is measured by photosensors **150,** compared to the desired level, and the current flowing through the selected LED adjusted accordingly. This method may be implemented using a single photosensor positioned so as to collect incident light from the LEDs.

[0016] In the second, preferred method, uses color filters over photosensors **150.** In this embodiment, a first pair of sensors, for example photosensors **150a** and **150c,** are covered with color filters which preferentially passes the shorter wavelengths, green through blue. Photosensors **150b** and **150d** are covered with color filters preferentially passing the longer wavelengths, green through red. Note that in this scheme, the passbands of each of the filters includes the green component. Alternatively, a separate channel with a green filter could be used. Note that when photosensors incorporating color filters are used, only those photosensors with similar filters are connected in parallel. In the example embodiment given, photosensors **150a** and **150c** would be connected in parallel, and photosensors **150b** and **150d** would be connected in parallel. In the embodiment using two channels, the proper color temperature is indicated by a set ratio between the outputs of the short and long wavelength sensors. The drive currents to the LEDs are adjusted to achieve the desired ratio. The overall device intensity is controlled by adjusting LED currents so that the sum of the signals from the short and long wavelength sensors equals a desired value.

[0017] The control circuit for the LED-sensor array may be a separate integrated circuit or circuits, and may be integrated onto the same substrate, or placed in separate packages.

[0018] In the preferred embodiment, the control circuit consists of integrators connected to each set of photodiodes; in this case, an integrator for the short wavelength sensors, and an integrator for the long wavelength sensors. These integrators convert photodiode current into a voltage representing the amount of light in that part of the spectrum. The voltage output of each integrator is fed to a window comparator. The purpose of the window comparator is to compare the input signal to a reference, and produce outputs when the input signal differs from reference by more than a specified amount of hysteresis. The reference is provided by an additional digital to analog converter (DAC). The gated outputs of the comparators are fed to up/down counters, which drive digital to analog converters. The digital to analog converters in turn control drivers for the LEDs.

[0019] This is shown in simplified form in Fig. **2.** Common circuitry such as initialization, gating, and clocking is not shown. Examining the red channel, photodiodes **150b,d** of Fig. **1** feeds op amp **210** which uses capacitor **220** to form an integrator. The output of the integrator, a voltage representing the amount of light flux from filtered photodiodes **150b,d,** feeds comparators **230** and **240.** The output of comparator **230** will be high if the output of integrator **210** is below reference voltage VR **250,** the desired red level. Similarly, the output of comparator **240** will be high if the output of integrator **210** is higher than reference voltage VR+ΔR **260.** Reference levels VR **250** and VR+ΔR **260** are provided by an additional digital to analog converter, not shown. The outputs of comparators **230** and **240** feed up/down counter **270.** The output of counter **270** feeds digital to analog converter (DAC) **280,** which feeds driver **290,** controlling the intensity of red LED **110.** While a field effect transistor (FET) is shown for driver **290,** bipolar transistors may also be used.

[0020] When the desired red light flux is below the desired level set by reference VR **250,** the output of comparator **230** will be high. Counter **270** counts up, increasing the value feeding DAC **280,** increasing the voltage on the gate of driver **290,** and increasing the brightness of LED **110.**

[0021] Similarly, if the desired red light flux is above the desired level set by reference VR+ΔR **260,** the output of comparator **240** is high, causing counter **270** to count down. This decreases the value sent to DAC **280,** decreasing the voltage on the gate of driver **290,** and decreasing the brightness of LED **110.**

[0022] The difference between reference voltages VR **250** and VR+ΔR **260** provides hysteresis in the operation of LED **110.** Its output will not be adjusted if it is within the window set by these two reference levels.

[0023] In the embodiment described, the output of

green LEDs **120** is not tracked, but instead is set by DAC **380** which feeds driver **390**, controlling green LEDs **120**. The overall intensity of the device is controlled through setting the green level, since the output of the red and blue LEDs will track in a ratiometric manner.

[0024] The blue channel operates in a manner similar to the red channel previously described. Red photodiodes **150a,c** feed integrator **410**. Integrator **410** feeds window comparators **430** and **440**, which compare the output voltage of integrator **410** representing the blue light flux to reference levels VB **450** and VB+ΔB **460**. The outputs of comparators **430** and **440** control up/down counter **470**, which feeds DAC **480** and driver **490** to control blue LEDs **130**.

[0025] By performing intensity measurements and adjustments over several measure - integrate - compare - correct cycles, changes are made in a gradual manner.

[0026] In this design, state information is held in the values of counters **270, 370, 470**. For more efficient startup, control circuitry would preserve the values of these counters across power cycles, restoring the counters to their last operating values as a good first approximation of starting levels.

[0027] The embodiment of Fig. **2** uses linear control to vary the intensity of the LEDs. DACs **280, 380**, and **480** generate analog levels feeding drivers **290, 390**, and **490**, controlling the intensity of LEDs **110, 120**, and **130**. Essentially, drivers **290, 390**, and **490** are being used as variable resistors. This type of arrangement is inefficient, as the voltage dropped across drivers **290, 390**, and **490** is turned into heat.

[0028] More efficient control is obtained by using switching converters to drive the LEDs. Switching converters are well known in the art, being manufactured by companies such as Texas Instruments and Maxim Integrated Circuits. As is known to the art, in a switching converter, varying pulse width or duty cycle is used to control a switch, producing an adjustable output voltage with very high efficiency. LEDs exhibit relatively high series resistance, so stable control of current is attainable by adjusting the voltage applied to the LED.

[0029] The embodiment of Fig. **2** is adapted to use switching converters by using the outputs of the window comparators **(230** and **240** for the red channel, **430** and **440** for the blue channel) to control the pulse widths for switching converters driving the LEDs. When a desired level is too low, the corresponding pulse width is increased, increasing the on time of the switching converter, increasing its output voltage, and increasing the corresponding LED current and luminous output. The values of counters **270, 370, 470** may be used to determine pulse width for the switching converters.

[0030] An additional embodiment illustrating these concepts is shown in Fig. 3. Sequencer **300** controls the operation of the device. Multiplexer **310** under control of sequencer **300** selects the output of one of the photodiodes **150b,d** or **150a,c**. The output of the selected photodiode is converted to digital form by ADC **320**.

[0031] Digital reference levels are provided by latches **410** for the red channel, **510** for the green channel, and **610** for the blue channel. The contents of these latches is loaded and updated by circuitry not shown. For the green channel, the output of latch **510** is used to set the pulse width of pulse width modulator **530**, producing a pulse width modulated output **540**, which is used to drive switching converter **550** to drive the green LEDs **120**.

[0032] Comparators **420** and **620** compare the output of ADC **320** to reference values **410** and **610**, respectively. The results of these comparisons, under control of sequencer **300**, are fed to pulse width modulators **430** and **630**, for the red and blue channels.

[0033] In operation, this embodiment performs much the same as its analog counterpart of Fig. **2**. Differences between measured values **(320)** and desired values **(410, 610)** are produced by comparators **(420, 620)** and increase or decrease the pulse width **(430, 630)** of the corresponding drive signals **(440, 640)**, driving switching converters **(450, 650)** and LEDs **(110, 130)**.

[0034] This embodiment has the advantage over the embodiment of Fig. **2** in that it is completely digital after the initial ADC stage **320**. The digital portion of Fig. **3** may be implemented in fixed logic, or in a single-chip microprocessor.

[0035] Fig. **4** shows a simple switching converter, here a step-down converter for use when the LED supply voltage (Vled) is higher than the voltage applied to the LEDs. Other topologies known to the art may be used to provide a boosted LED voltage if needed by the particular implementation without deviating from the spirit of the current invention. Pulse width modulated drive signal **440** drives the gate of MOS switch **200**. When switch **200** is turned on, voltage is applied across inductor **220**, causing current to flow through the inductor. When switch **200** is turned off, current continues to flow in inductor **220**, with the circuit completed by catch diode **210**, preferably a Schottky diode. The voltage across LED **110** is smoothed by capacitor **230**. The voltage across LED **110** is proportional to the on-time of switch **200**, and therefore the pulse width of drive signal **440**.

[0036] The foregoing detailed description of the present invention is provided for the purpose of illustration and is not intended to be exhaustive or to limit the invention to the precise embodiments disclosed. Accordingly the scope of the present invention is defined by the appended claims.

Claims

1. A solid state illumination device (100) for producing a predetermined spectral distribution comprising:

   a plurality of light emitting diodes (110, 120, 130) of different colors,
   a photosensor (150) measuring incident light

from the light emitting diodes,
the light emitting diodes and photosensor connected to a control circuit comprising:

a plurality of driver means (290, 390, 490, 450, 550, 650), each driver means driving one or more light emitting diodes of a predetermined color,
comparison means (230, 240, 430, 440, 420, 630) for comparing the output of the photosensor with the predetermined spectral distribution, and,
adjustment means (270, 470) coupled to the comparison means for adjusting the driver means such that the output of the photosensor matches the predetermined spectral distribution.

2. The illumination device of Claim 1 where the photosensor (150) is mounted interspersed among the light emitting diodes (110, 120, 130) so as to measure incident light from the light emitting diodes.

3. The illumination device of Claim 1 or 2 where the photosensor (150) is a photodiode.

4. The illumination device of Claim 1, 2 or 3 where the driver means (290, 390, 490) is a linear driver.

5. The illumination device of Claim 1, 2 or 3 where the driver means (450, 550, 650) is a switching converter.

6. The illumination device of one of the preceding claims where the photosensor (150) responds to the light emitted by each of the different color LEDs (110, 120, 130).

7. The illumination device of one of the preceding claims where the photosensor (150) and the light emitting diodes (110, 120, 130) are mounted on a common substrate.

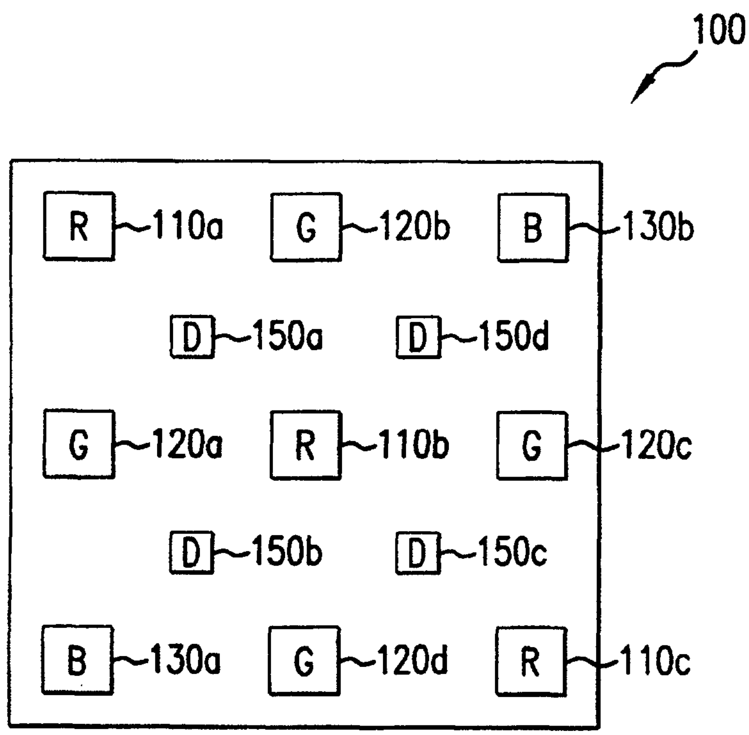

100
R
110a
G
120b
B
130b
D
150a
D
150d
G
120a
R
110b
G
120c
D
150b
D
150c
B
130a
G
120d
R
110c

FIG.1

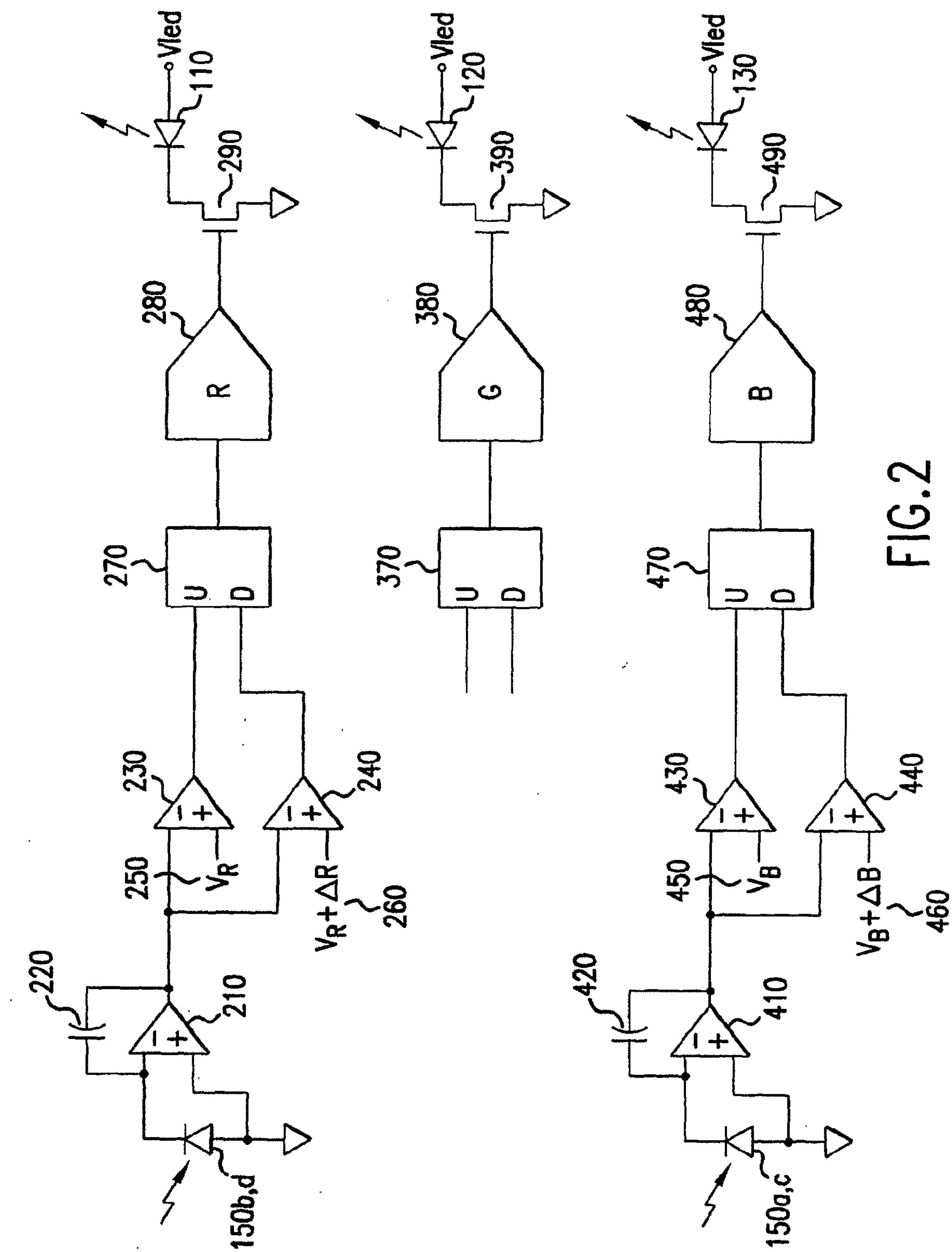
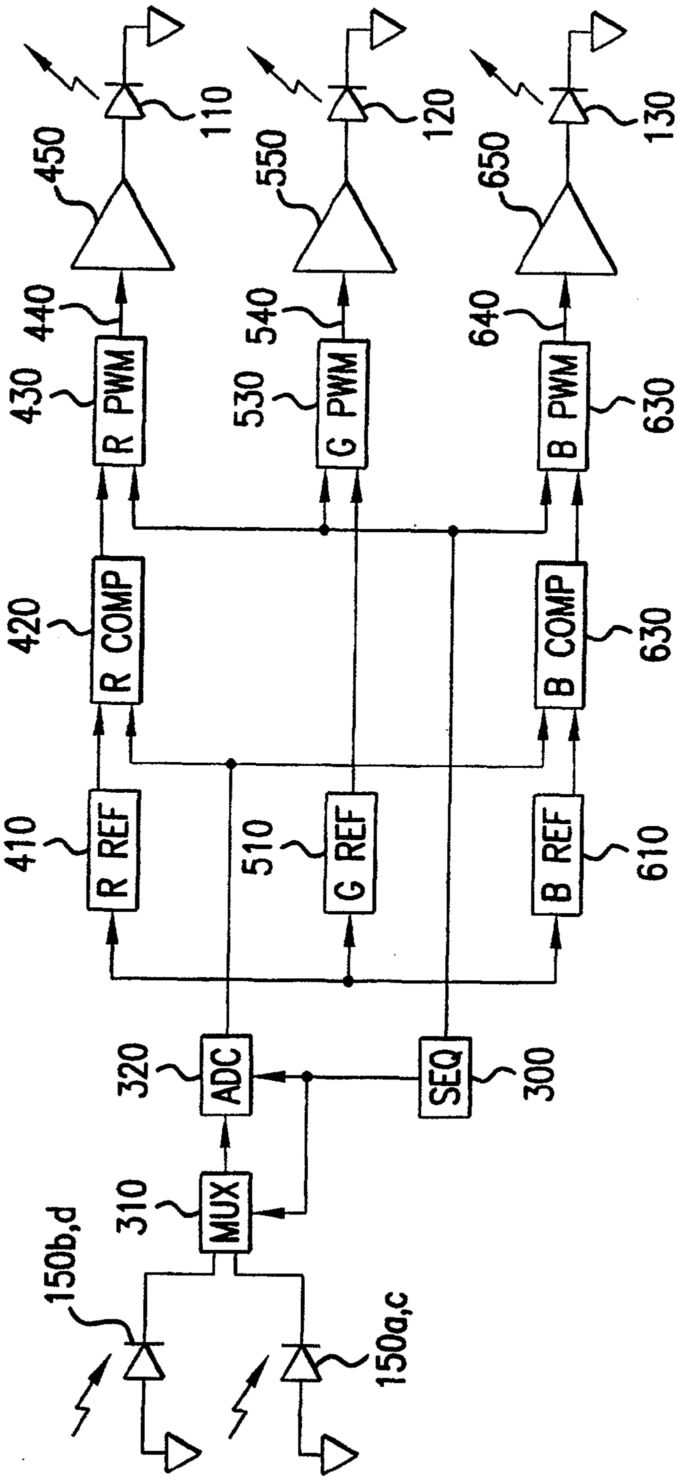

Vled
110
Vled
120
Vled
130
290
390
490
280
R
380
G
480
B
270
U
D
370
U
D
470
U
D
230
240
430
440
250
V_R
$V_R+\Delta R$
260
450
V_B
$V_B+\Delta B$
460
220
210
420
410
150b,d
150a,c

FIG.2



150b,d
150a,c
310
MUX
320
ADC
SEQ
300
410
R REF
510
G REF
B REF
610
420
R COMP
B COMP
630
430
R PWM
530
G PWM
B PWM
630
440
540
640
450
550
650
110
120
130

FIG.3

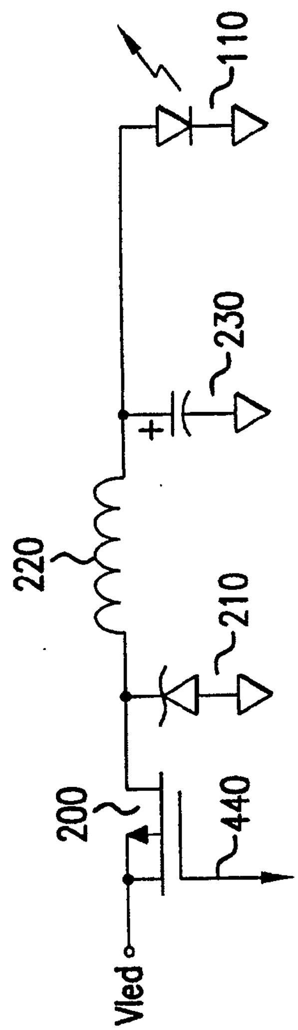


FIG.4

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(12) **EUROPEAN PATENT APPLICATION**

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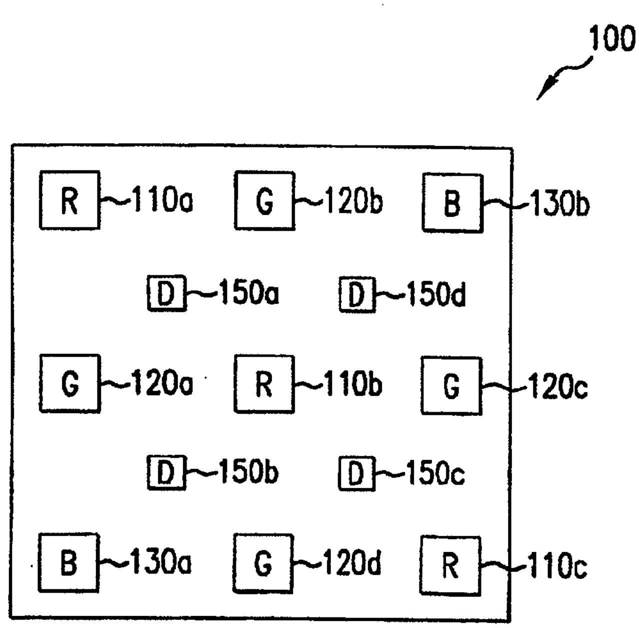

FIG.1

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EUROPEAN SEARCH REPORT

Application Number
EP 01 10 9868

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	3 September 2003	Albertsson, E

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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